



Friction Stir Scribe Joining of Carbon Fiber Reinforced Polymer to Aluminum

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Project ID# LM114

Overview

Project Timeline

- Project Start Date: January 1, 2016
- Project End Date: June 31, 2018
- Percent Complete: 60%

Budget

- Total project funding
 - DOE share: \$609,473
 - Contractor share :\$1,608,687
- Funding received in FY16: \$119,458
- Funding for FY17:
 - DOE share: \$313,289
 - Contractor share: \$810,899

Participants

- General Motors LLC – Lead
- Pacific Northwest National Lab (PNNL)
- Kuka Systems North America – Sub-Recipient
- Arconic – Sub-Recipient
- Plasticomp – Sub-Recipient
- Autodesk – 3rd party in-kind contributor
- Livermore Software Technology Corporation (LSTC) – 3rd party in-kind contributor

Barriers Addressed

- Joining and Assembly: High-volume, high-yield joining technologies for lightweight and dissimilar materials needs further improvement. (VT Multi-Year Program Plan 2.5.1F)
- Ability to create a continuous, complex 3-D linear joint in a production like environment is not developed.
- Excessive levels of FSSJ tool wear by the CFRTP material based on common tool steel compositions.



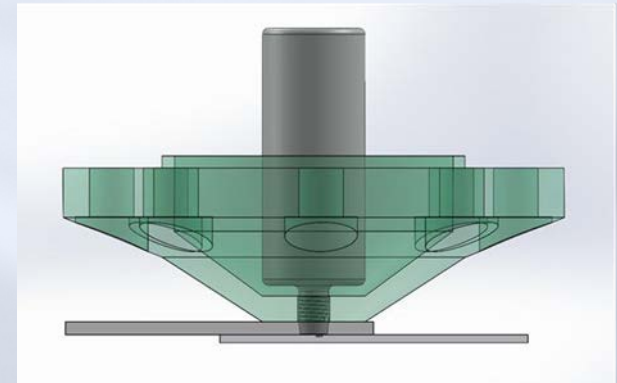
Relevance

Project Goal

- Demonstrate novel multi-material solid state joining technology for application of Carbon Fiber Reinforced Composite Thermoplastics to Aluminum on industrially relevant components based on process development and numerical simulation performed at scale. (addressing technology gap (3.1.2)¹)

Project Objectives (FY 2016-2017)

- Integration of Friction Stir Scribe tool with a Stationary Shoulder
- Demonstrate targeted mechanical properties of the produced joints (> 70% of the weakest base equivalent tensile strength)
- Develop the critical process technology, models and tools necessary to advance the FSS method through experimentation, validation at the laboratory scale, and integration into a production-like robotic environment.



¹Light-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials, Workshop, pp26, 2013, US DOE VTO

Relevance

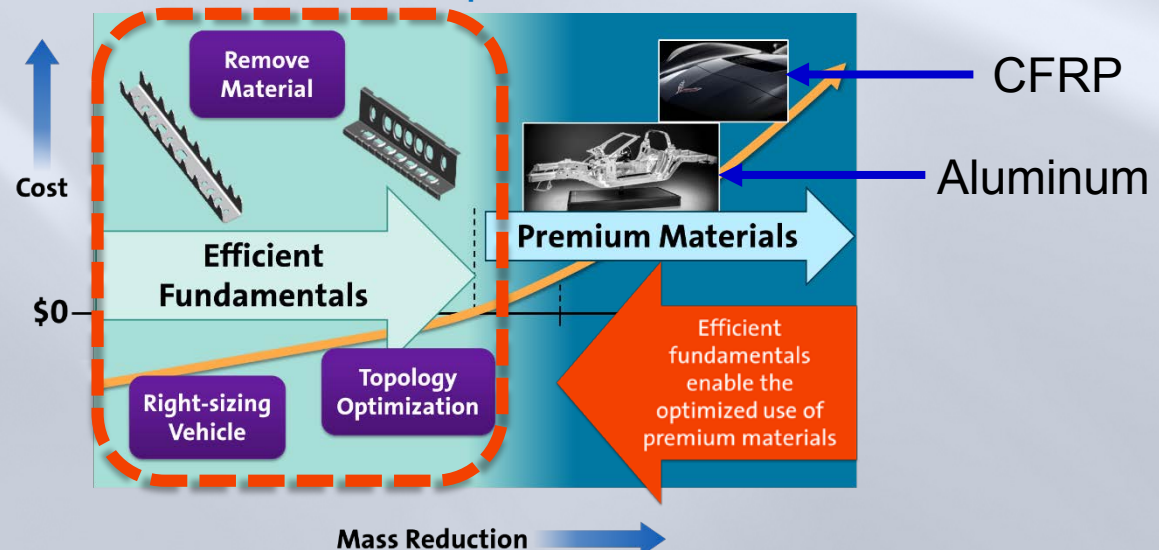
Regulatory requirements

OUTLOOK FOR GLOBAL FUEL ECONOMY AND GREENHOUSE GAS regulations

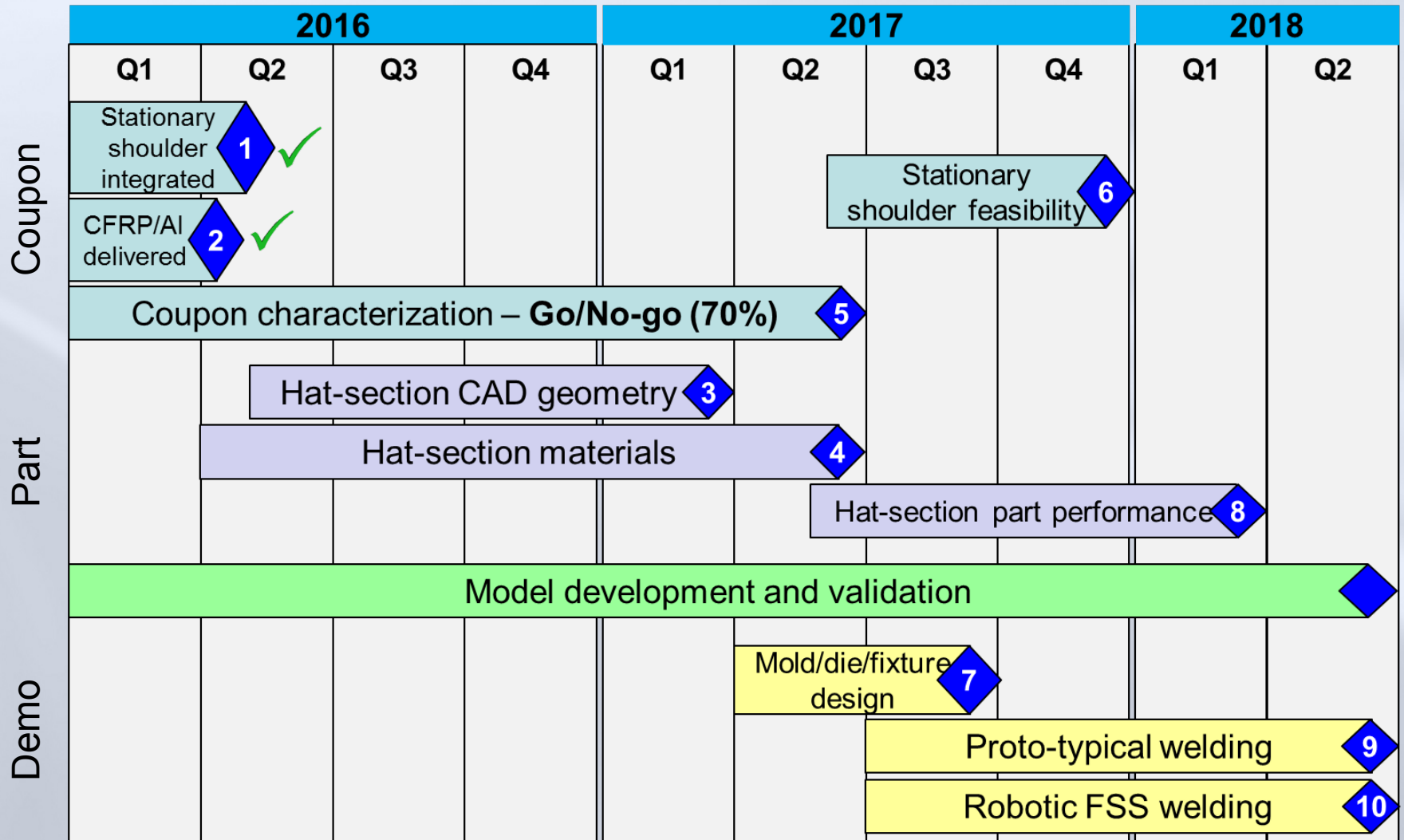
	MPG	YEAR
United States	54.5	2025
Europe	58.0	2020
China	56.0	2020

Lightweighting Strategy

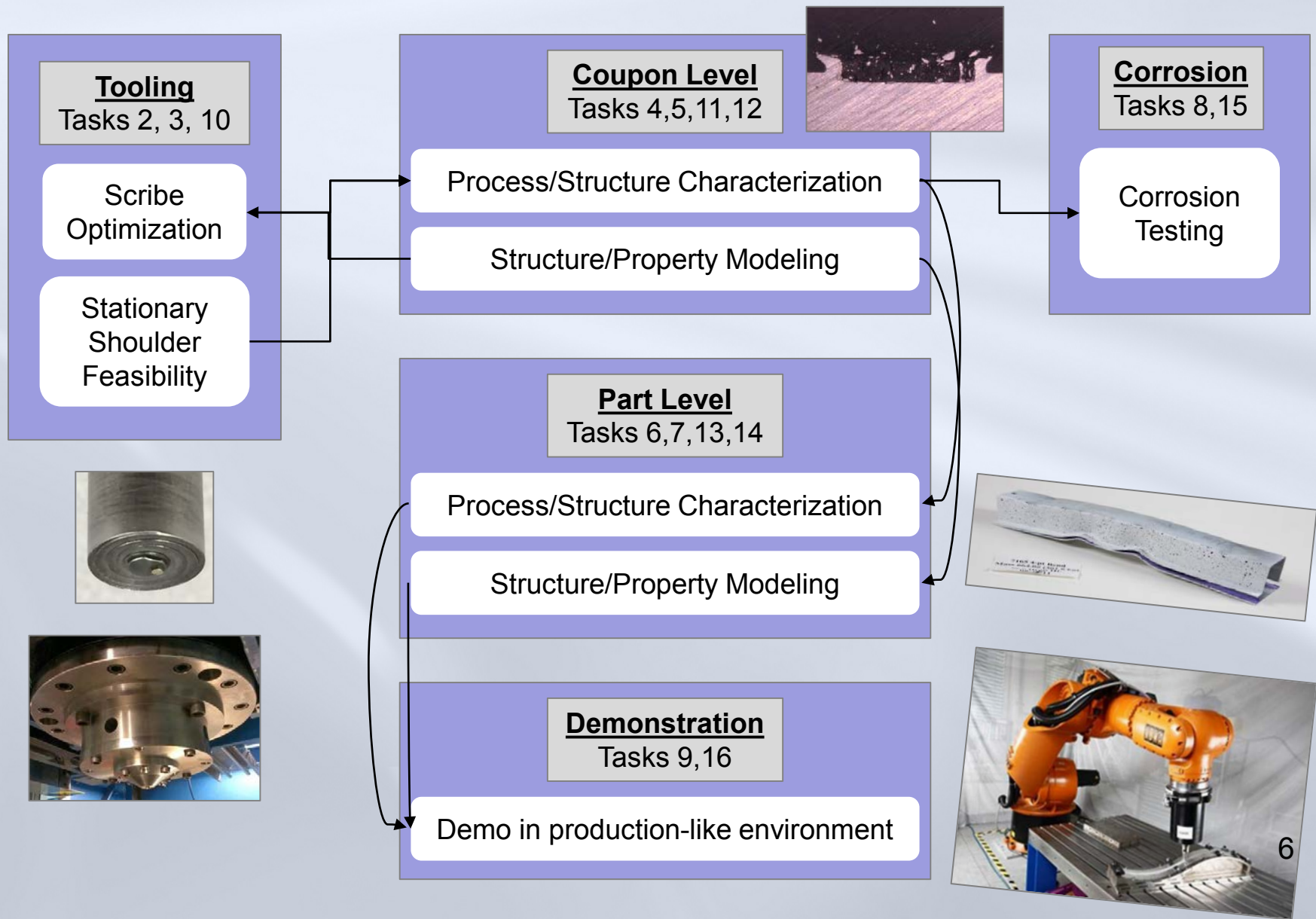
Practice Efficient Fundamentals to enable optimized use of mixed materials



Project Milestones



Approach Strategy

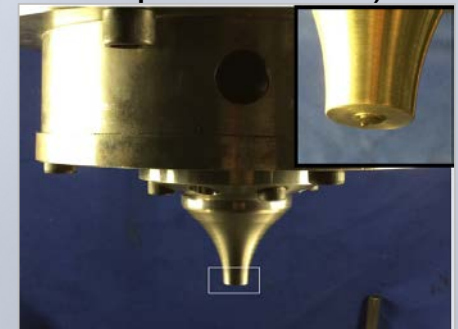


Technical Approach

- The project utilizes a solid state joining (no melting) method called friction stir scribe, which is capable of joining materials with different melting regimes to produce viable joints between automotive carbon fiber reinforced thermoplastic, CFRTP, and aluminum sheets.
- The application of this technology on a 3D robotic platform will be augmented by the development, validation and integration of predictive modeling tools to aid in complete predictive engineering of molded CFRTP structures that are subsequently joined to aluminum alloys for a fully integrated application.

Tooling

- Start with traditional rotating shoulder tool
- Optimize Scribe geometry & location (leverage DOE funded FSSJ of Al to Steel project)
- Integrate Scribe tooling with Stationary Shoulder (provides less heat input to CFRP)
- Feasibility of Stationary Shoulder on 3-D robotic application



Technical Approach

Process/Structure Characterization

- Measure fiber orientation in molded CFRP plaques to validate Moldflow simulation
- Complete DOE to identify best FSSJ tool material in regards to wear/erosion by C-fibers
- Minimize FSSJ tool (pin and shoulder) diameter
- Complete DOE to define optimum FSSJ process parameters
- Characterize microstructures of base materials and weld zone (fiber length)

Structure/Property Modeling

- Model flow of CFRP during injection molding to define fiber orientation
- Measure material & mechanical properties of base materials and weld zone
- Predict hook formation and correlate to coupon level joint performance
- Model performance of Part level component and Demonstration assembly

Corrosion

- Experimental Measurements (e-coat &/or adhesive)
 - Electrochemical potential of base materials
 - Conventional salt spray corrosion testing followed by qualitative evaluation & Lap-Shear testing

Demonstration

- Use Wheelhouse opening as basis to develop stamping tool & CFRP mold
- Transfer process parameters of coupon/part-level component to Demonstration assembly
- Investigate feasibility of stationary shoulder on a 3-D linear welding path

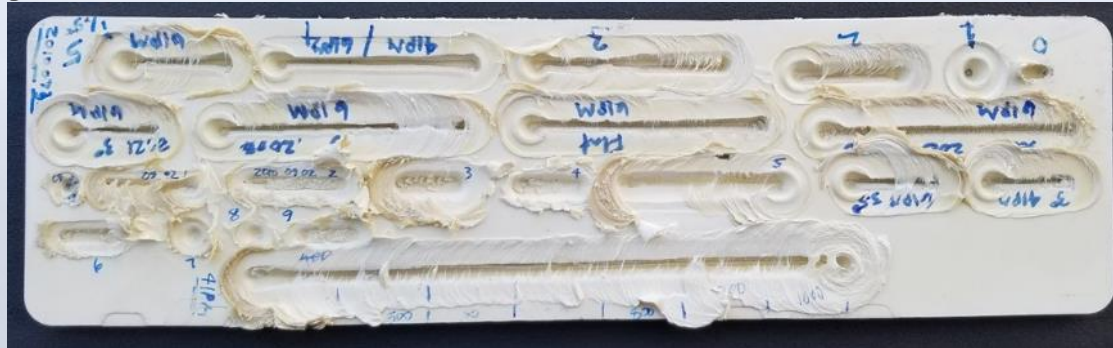
Project Schedule and Progress

	Tasks	FY 2016				FY 2017				FY 2018	
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q1	Q2
	Scribe optimization	(100%)									
	Stationary shoulder										
✓ FY 16 milestone	Integration with scribe tool	(100%)									
FY 17 milestone	Stationary shoulder feasibility results										
✓ FY 16 milestone	Weld Process and structure-property characterization	(100%)									
Go/No-go	Decision gate (Joint strength = 70% of weakest base material)	Actual = 13%									
	Corrosion			(80%)							
	Hat-section										
○ FY 16 milestone	Design and geometry		(95%)								
○ FY 16 milestone	Deliver materials		(60%)								
FY 17 milestone	Hat section part performance evaluation										
	Process and structure –property modeling		(60%)								
	Prototype and 3D Demo										
FY 17 milestone	Mold/die/fixture design										
FY 17 milestone	Proto-typical welding										
FY 17 milestone	Robotic FSSW										

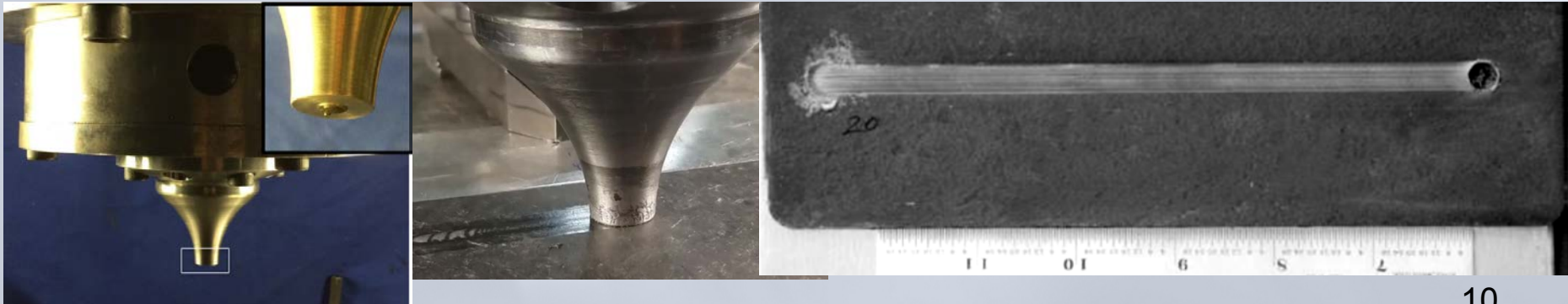
Technical Accomplishments

Integration of Friction Stir Scribe tool with stationary shoulder

- Conventional rotating shoulder creates excessive thermal energy – results in channeling and excessive flash.



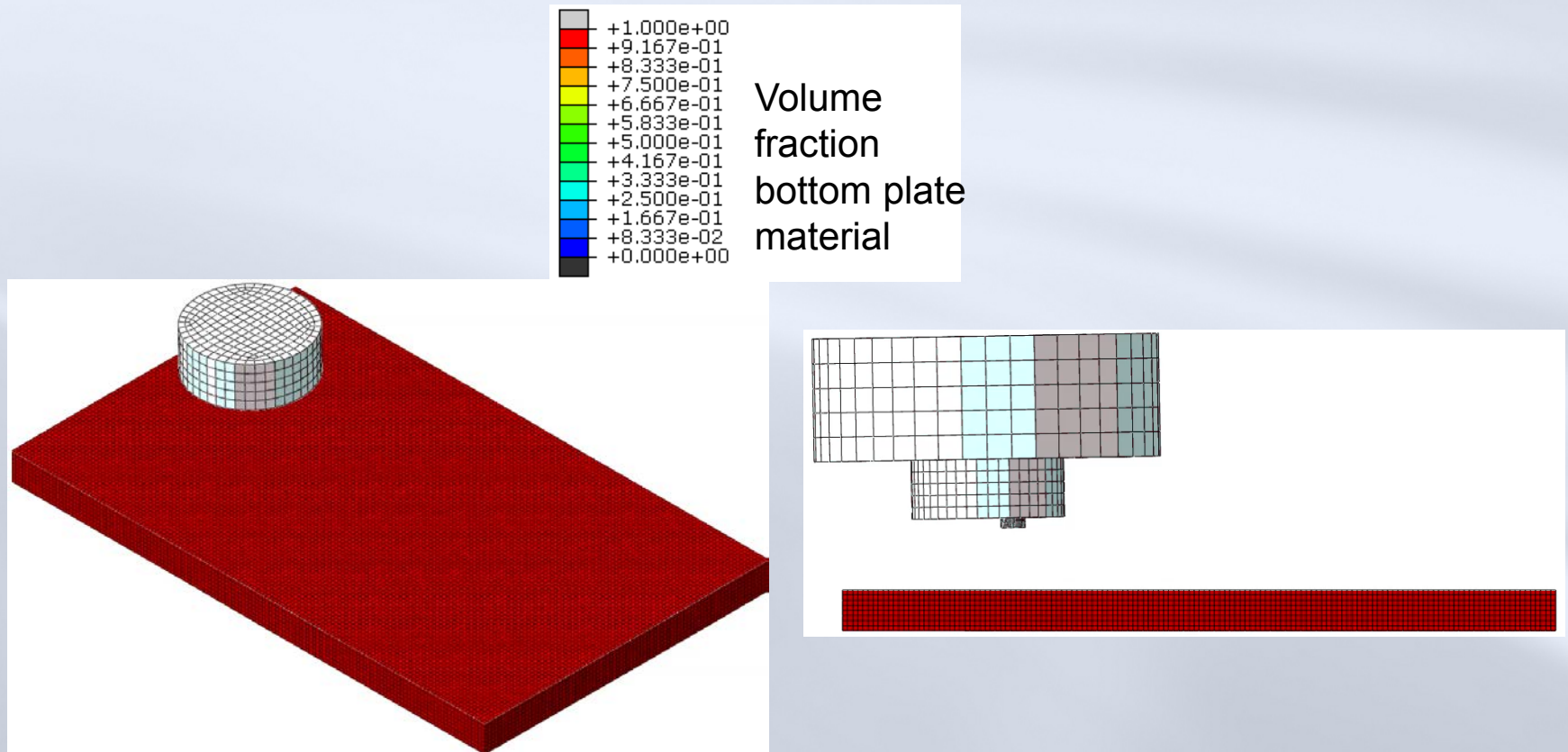
- The stationary shoulder has been successfully integrated with the friction stir scribe (FSS) tool at PNNL.



Stationary shoulder results in excellent welds

Technical Accomplishments

Numerical Modeling of FSSJ Process

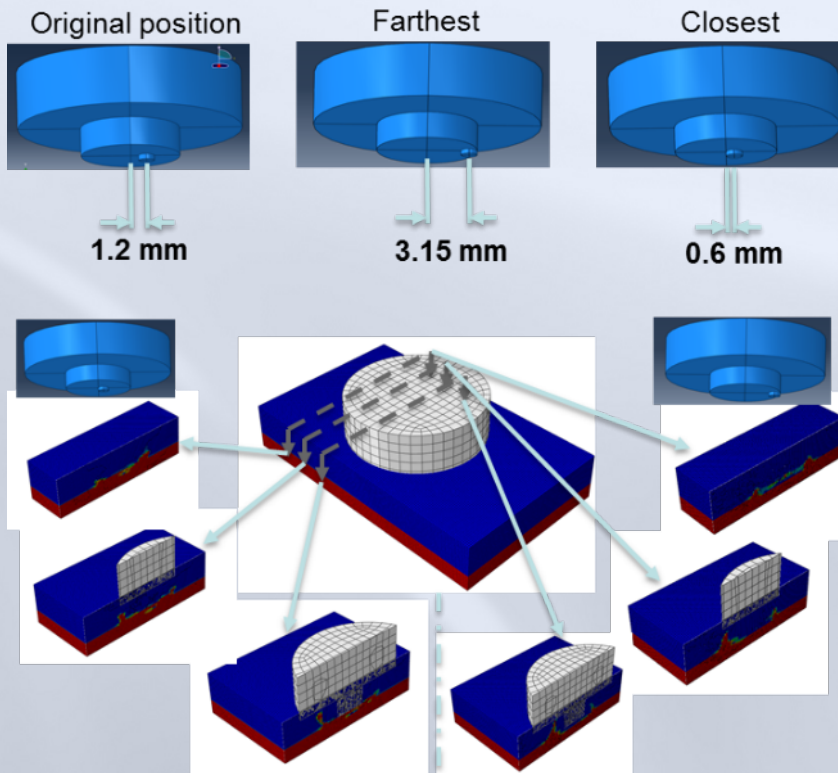


Interaction of FSSJ with bottom plate only. Cutting action of the scribe induces deformation leading to *hook* formation.

Technical Accomplishments

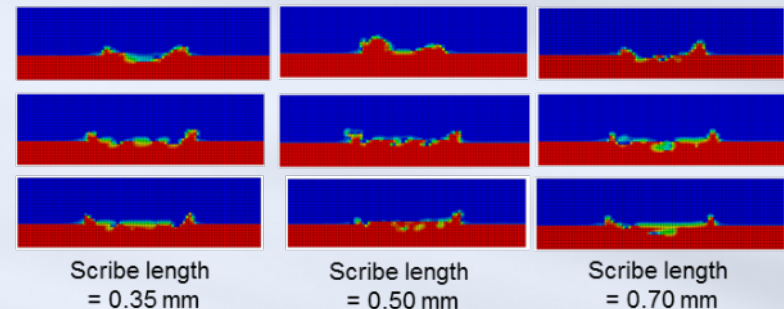
Scribe Optimization via Modeling

Scribe radial position

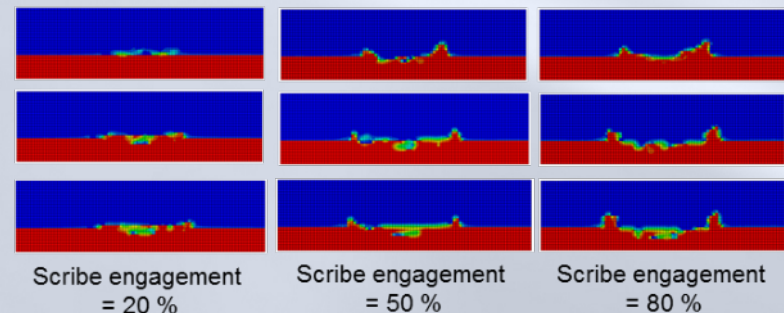


Scribe closer to center →
better hook morphology

Scribe length and engagement



Different scribe lengths, same engagement (50%)



Different scribe engagements, same length (0.7 mm)

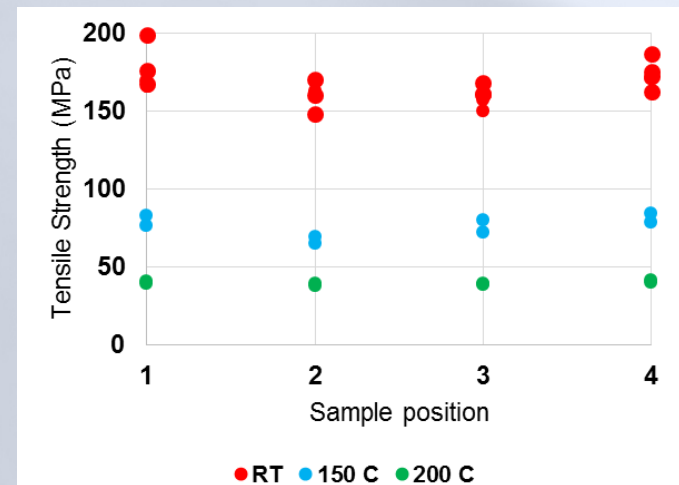
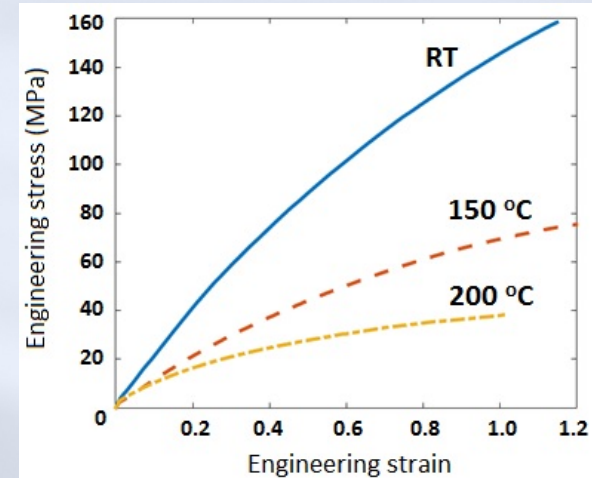
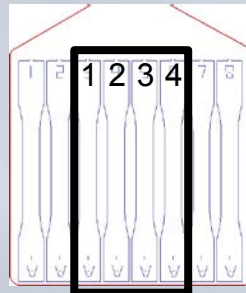
Higher scribe engagement →
better hook morphology

Technical Accomplishments

Measured Temperature Dependent CFRP Mechanical Properties as Input to Model

Temperature (°C)	Tensile strength (MPa)	Modulus (MPa)
RT	169 ± 13.3	19338 ± 2683
150	76.1 ± 6.9	11553 ± 1023
200	39.8 ± 1	8917 ± 935

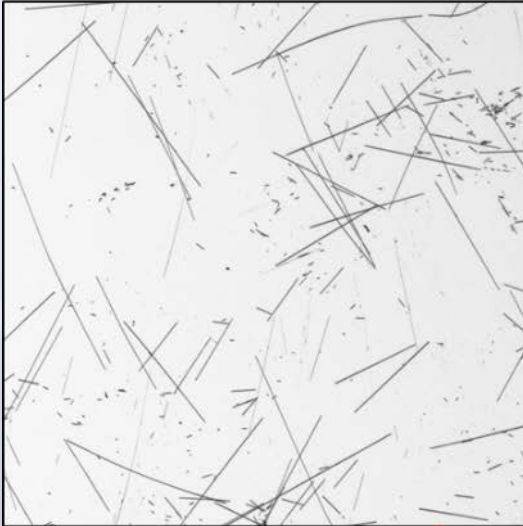
- Temperature dependent mechanical properties established for CFRP & Al.
- Also measured Barlat 2000 yield function parameters for Al.



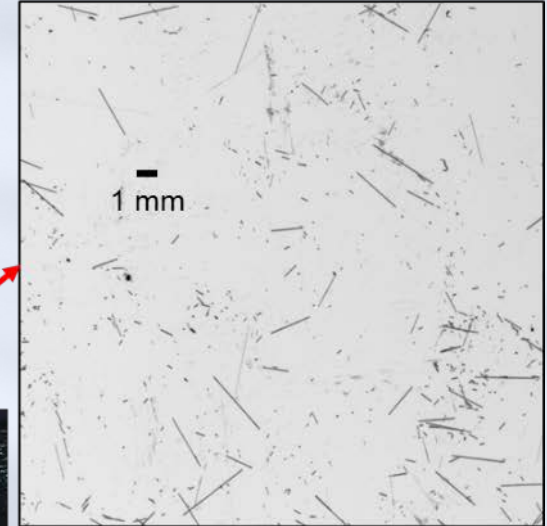
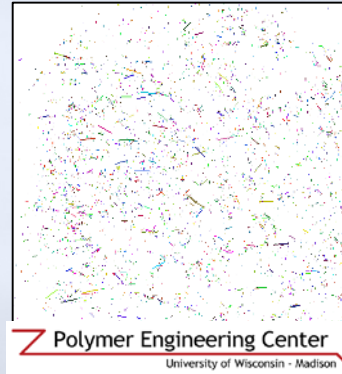
Technical Accomplishments

Identified best practice for fiber length measurement & characterized weld zone CFRP microstructure & properties.

$L_n = 0.42$ mm



Tensile strength =
 169 ± 13 MPa



Tensile strength =
 60 ± 3 MPa

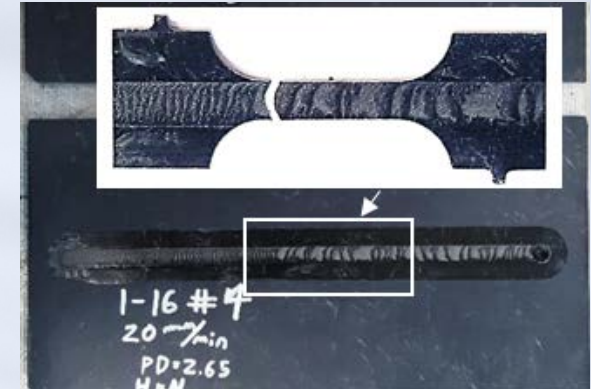


- Severe fiber attrition during friction stir → CFRP weld zone is the weak link.
- Fiber length a function of tool RPM & translation speed.

Speed	RPM	L_n (mm)
20	1650	0.262
30	1650	0.189
20	1950	0.310
30	1950	0.244

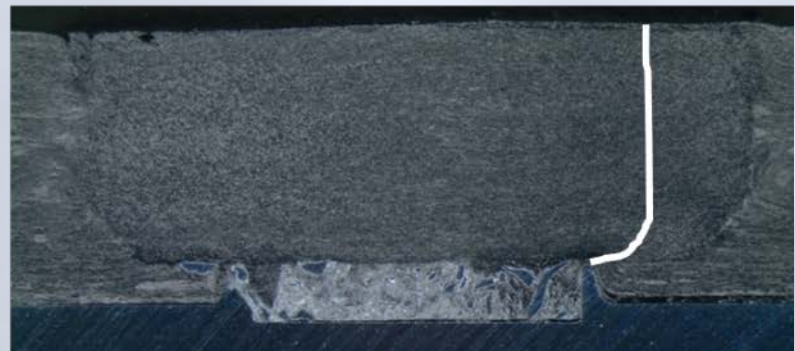
Technical Accomplishments

Lap-Shear Strengths & Fracture Mode Identified as well as Weld Zone Properties Measured



Crack initiates at the tip of the hook.

Crack propagates straight up through thickness, within the weld nugget.



Crack initiation at hook tip + weak CFRP weld zone → Fracture through nugget → Low joint strength

Responses to Previous Year Reviewers' Comments

- This project is being reported for the first time

Collaboration & Coordination

➤ Participants

- Arconic: Al sheet materials & properties
- Plasticomp: CFRP material, mold design, molding of parts
- PNNL: Optimized scribe tool & process parameters
- PNNL: Material characterization & model development
- GM: CFRP fiber orientation, corrosion testing & material property testing
- LSTC: LS-Dyna software & technical support
- Autodesk: Mold flow software, CFRP rheological property measurements
- GM: Tooling design & build, validation of process window
- Kuka: Robotic friction stir scribe joining of proto-typical part

➤ Academic Collaboration

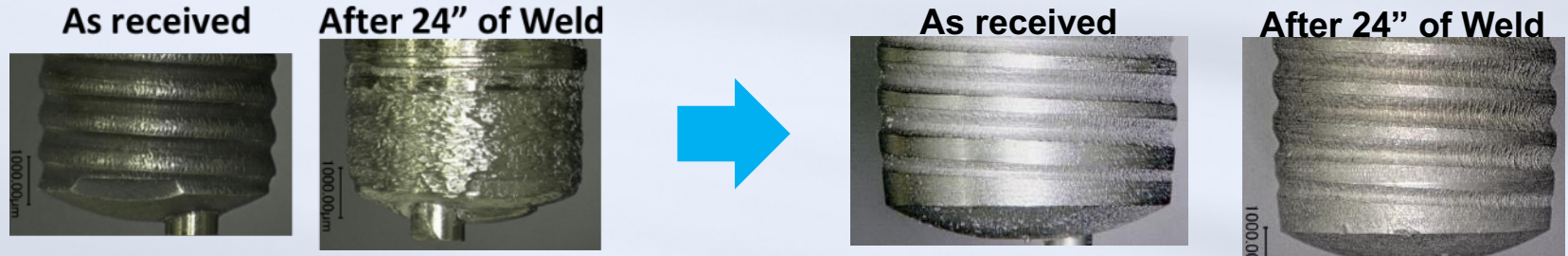
- Virginia Polytechnic Inst: CFRP fiber length (burn-off & imaging)
- University of Wisconsin: Image analysis of fiber length measurements

➤ Leverage

- DOE funded project Friction Stir Scribe Joining of Aluminum to Steel
- DOE funded project Predictive Models for CFRP Components

Remaining Challenges & Barriers

➤ Excessive Tool Wear (complete DOE) A11 Tool Material

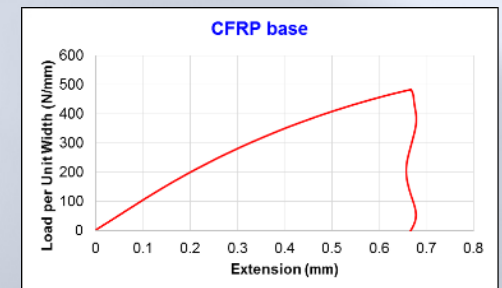
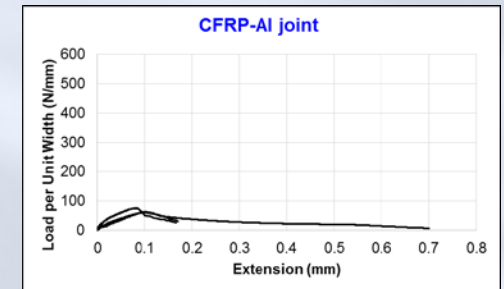


➤ 70% Joint Strength Target (Actual = 13%)

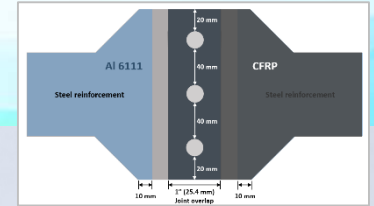
- Attempting FSSJ plunge through Al vs CFRP

➤ 3-D robotic linear welding

- Complex tool path for welding



Proposed Future Research



- Super lap joint testing as a means to compare joint strengths of FSSJ to known solutions (alternative to 70% of base material strength)
- Investigate Tool Plunge from Al side vs CFRP side (goal is to mitigate low strength of stirred CFRP material)
- Identify tool wear as a function of material



- Validation of process-structure model
- Evaluation of potential CFRP/Al corrosion approaches
- Development of 3-D linear FSSJ with stationary shoulder

- **H13** - hot work steel (baseline for comparison)
- **CPM 10V (A11)** - wear-resistant tool steel
- **Ferro-Tic** – steel bonded TiC
- **Stellite 6B** – Co-based, Cr-W alloy
- **SiN** – ceramic Si₃N₄
- **WC** – Sandvik K10, TMK-320 or similar
- **PCBN** – polycrystalline cubic boron nitride
- **PCD** – polycrystalline diamond

Summary

- Demonstrated feasibility of integrating a friction stir scribe tool into a stationary shoulder.
- Highlighted the requirement of a stationary shoulder for high quality friction stir scribe joining of CFRP to Al (assuming plunge through the CFRP).
- Validated simulation of the injection molded CFRP plaques by experimental measurements.
- Developed FSSJ model and applied it to define optimum scribe location.
- Applied unique image analysis technique to fiber length measurements.
- Identified tool wear (i.e. not scribe durability) as a limiting factor which requires materials other than H13 tool steel.
- Static strength of the FSS joints exhibited less than half of the targeted Go/No-Go threshold.

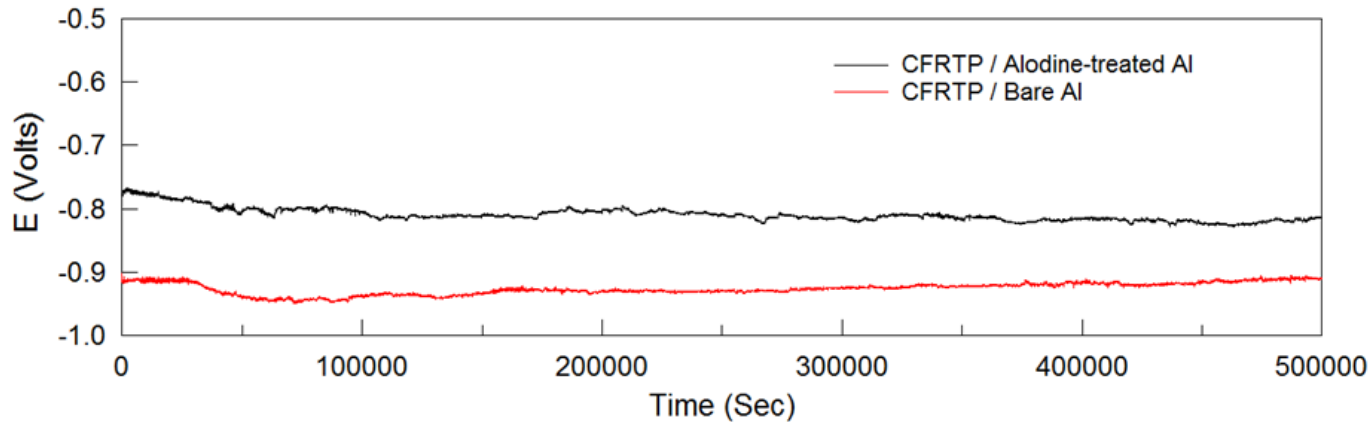
Technical Back-up Slides

Strength Comparisons

Type of test	Material description	Average strength (MPa)	Max load per unit width (N/mm)	Strength normalized with base CFRP (%)
Mini-tensile of CFRP from weld nugget	Parallel to weld direction	60.4 ± 2.6	113.8 ± 5.3	22.3
Tensile test of base CFRP plaque	Middle of plaque 0° to flow	170 ± 14.4	510 ± 43.2	100
Tensile test of bead-on-plaque weld transverse to the weld direction	1000 RPM, 30 mm/min		85.9 ± 8.7	16.8
	1500 RPM, 50 mm/min		70.4 ± 20.2	13.8
Lap shear test of CFRP-Al weld (Ø 7.5 mm pin, Ø 30 mm shoulder)	1000 RPM, 50 mm/min		49.8 ± 4	9.8
	1900 RPM, 50 mm/min		67.3 ± 6.4	13.2
Lap shear test of CFRP-Al weld (Ø 5.4 mm pin, Ø 18 mm shoulder)	1950 RPM, 20 mm/min		36.3 ± 3.7	7.1
	1900 RPM, 20 mm/min		37.9 ± 2.6	7.4
Guided lap shear test of CFRP-Al weld			61.6 ± 4.6	12.1

Corrosion Measurements

- Galvanic corrosion between Al and CFRTP in 3.5 wt.% NaCl solution



Alodine treated Al alloy couple combination has less galvanic effect compared to bare Al alloy couple

